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13. ABSTRACT (Maximum 200 words)

We performed a theoretical feasibility study of a conceptually new infrared photon detector. The operational principle of the detector is based on a 3-level quantum coherence effect. The study involved 3-level quantum coherence effects with incoherent (thermal) light in semiconductor quantum dots and the optimization of the detected signal. We were mainly concerned with one specific design concept, namely the one based on an interferometric waveguide geometry. The infrared light couples the two lowest conduction band states in the quantum dot, and an auxiliary coherent laser light beam couples the valence band states with one of the conduction band states. We have performed detailed theoretical studies of the noise properties of the detector. Specifically, we have investigated the noise due to vacuum fluctuations of the infrared light in the interferometer. We have also studied the temperature dependence of the noise-equivalent power. An estimate of the normalized detectivity D* at room temperature yields 5 X 10^6 cm sqrt(Hz)/Watts.

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Statement of the problem studied

This project was a theoretical study of a conceptually new infrared photon detector. This detector is based on a quantum-interference effects in semiconductor quantum dots similar to effects well-known in atomic 3-level systems. The three quantum dot levels involved in the detection scheme were chosen to be one valence band level and two conduction band levels. In this case, the thermal infrared light couples the two conduction band levels, and quantum interference can be detected with an auxiliary laser field that is weak and fully coherent and that couples the valence band level to one of the two conduction band levels. While this concept is, in principle, a good concept (because it would make the infrared detection almost completely temperature independent and, at the same time, would allow for very fast detection), the main shortcoming of the concept is related to the fact that the intensity of the incoming IR light is very low. Therefore, this study was mainly concerned with the optimization of the detectable signal. We have proposed various designs in the original ARO proposal that led to this project, including quantum dots in an interferometric waveguide geometry. One of the main goals of this project was to calculate performance characteristics of the detector.

This project began as a "spin-off" project of our investigation of coherent 3-band effects in semiconductor quantum wells (not quantum dots). That project, which is sponsored in part by JSOP, has been very successful. In particular, we have successfully analyzed and interpreted experimental four-wave mixing signals from semiconductor quantum well microcavities [1,2]. The analysis was based on a fully microscopic theory that includes excitons and coherent biexcitons in semiconductor quantum wells, and was extended to account of inhomogeneous broadening and line-shape asymmetries [3]

We have used a similar theoretical approach to predict signatures of 3-band quantum interferences (similar to the ones underlying the detector scheme) via the coherently-coupled heavy-hole-light-hole optical Stark effect in semiconductor quantum wells. Our combined theory-experiment investigation demonstrated clearly the similarities between Raman coherences in atomic level systems and corresponding non-radiative coherences (here: intervalence band coherences) in semiconductor quantum wells [4]. Note that electromagnetically-induced transparency (EIT) and other 3-level effects depend on the existence of a Raman coherence and that a demonstration of an intervalence band coherence (or other non-radiative coherences) is a necessary step toward the realization of EIT-like phenomena in semiconductor quantum wells.

Summary of the most important results

The most important results regarding our analysis of the quantum-interference IR detector are as follows.

We have performed a detailed noise analysis of the design based on a Mach-Zehnder interferometer using balanced homodyne detection. In doing so, we assume that the dominant noise source is the shot noise due to vacuum fluctuations of light with frequency close to that of the auxiliary laser light beam. This assumption is supported by the relatively large noise-equivalent power (NEP) which we predict on the basis of the noise considered in our simulation. We have derived a general formula for the signal-to-noise ratio and the NEP for the Mach-Zehnder quantum dot quantum interference IR detector. Based on that formula, we have calculated the NEP using idealized but not at all unrealistic parameter values. The parameters for the quantum dot density in the fiber has been chosen to correspond to an inter-dot distance of 500 Angstrom, which is a moderate and realistic density for dots with typical dot diameters of 80 Angstrom. The length of the quantum-dot loaded arm of the interferometer was chosen to be 10 cm. The NEP was found to be a function of temperature and of the wavelength lambda_23 of the IR transition in the quantum dot (the transition between the two conduction band states). Specifically, at room temperature we find a strongly non-monotonic behavior of the NEP as function of lambda_23, with a minimum of the NEP at around 10 microns. For these parameter values, the calculated NEP is about 0.2 W/cm^2. We believe that proper focusing of the incoming IR light (e.g., focusing a 1cm^2 spot down to approximately (10 micron)^2) could yield IR intensities that are close to or exceed the NEP. Furthermore, an estimate of the normalized detectivity D* at room temperature yields 5 X 10^6 cm sqrt(Hz)/Watts. This is similar or even exceeds that of competing PEM detectors, which are also high-speed room-temperature detectors, but which require permanent magnets.

We have submitted our performance analysis of the quantum-interference IR detector for publication [5]. We anticipate additional future publications that contain more details about the analysis as wells as further simulations of performance characteristics.

Personnel Supported

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[1]References 1-4 are related publications supported by JSOP. Reference 5 is based on the research reported here and supported by ARO.